# SAMMI: A Spatially-Aware Multi-Mobile Interface for Analytic Map Navigation Tasks

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**ABSTRACT**

Motivated by a rise in the variety and number of mobile devices that users carry, we investigate scenarios when operating these devices in a spatially interlinked manner can lead to interfaces that generate new advantages. Our exploration is focused on the design of SAMMI, a spatially-aware multi-device interface to assist with analytic map navigation tasks, where, in addition to browsing the workspace, the user has to make a decision based on the content embedded in the map. We focus primarily on the design space for spatially interlinking a smartphone with a smartwatch. As both smart devices are spatially tracked, the user can browse information by moving either device in the workspace. We identify several design factors for SAMMI and through a first study we explore how best to combine these for efficient map navigation. In a second study we compare SAMMI to the common Flick-&-Pinch gestures for an analytic map navigation task. Our results reveal that SAMMI is an efficient spatial navigation interface, and by means of an additional spatially tracked display, can facilitate quick information retrieval and comparisons. We finally demonstrate other potential use cases for SAMMI that extend beyond map navigation to facilitate interaction with spatial workspaces.

**Author Keywords**

Spatial interaction; Around-Device Interaction; Peephole Interaction; Ubiquitous Analytic Interfaces.

**ACM Classification Keywords**

H.5.2. Information interfaces and presentation (e.g., HCI): User Interfaces – Interaction styles.

**INTRODUCTION**

Analytic map navigation tasks that involve browsing a map for retrieving and comparing various information bits to make a decision often require users to re-inspect previously visited items [14,35]. As revisitation can be tedious and time consuming [1,13,35], map interfaces support different techniques such as bookmarking to 'log' previously inspected items. However, keeping track of all logged information while navigating the workspace can be in-efficient as it imposes additional cognitive load, breaks the seamless interaction and forces the user to switch between the map and bookmarked content [35]. These challenges are amplified on mobile devices with small displays.



As users advance toward an ecosystem of multiple mobile devices (a survey of 2,226 users [18], indicates that people carry on average 2.9 devices), we investigate whether using more devices and their screens in a spatially interlinked manner can lead to interfaces that generate new advantages. To this end, we propose SAMMI (Spatially-Aware Multi-Mobile Interface), an interface that supports users' analytic map navigation tasks with two spatially-aware mobile devices: a smartphone and a smartwatch. With SAMMI, directly pointing at a map around a smartphone, as shown in Figure 1, can make relevant content appear on the watch, mitigating content occlusion problems and the need for an overview [14]. Alternatively, the user can browse the workspace by sliding the watch or the phone in the workspace. We tailor the design of SAMMI to specifically assist with complex analytic map navigation tasks as these are not as easily managed with standard mobile interfaces.

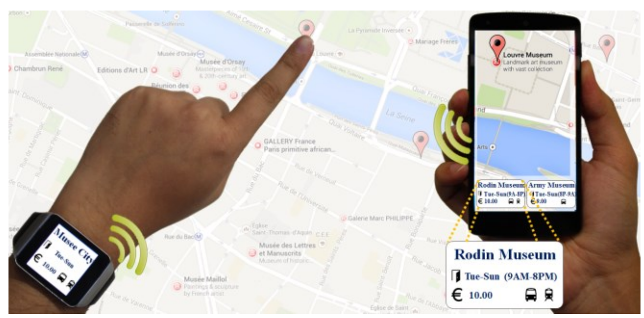


**Figure 1. SAMMI uses two spatially-aware smart-devices to facilitate navigating a large workspace. One device, e.g., a smartwatch, can be used to quickly retrieve workspace information. Such information can be pinned to the other device (e.g., a smartphone) for later access.**

Our exploration offers the following contributions: (i) SAMMI, an interface based on the spatial interlinking of mobile devices, and in our exploration we limit this to the use of a smartphone with a smartwatch; (ii) a refinement of SAMMI's design elements; and (iii) a demonstration that spatially-aware and connected mobile devices can facilitate complex analytic tasks with spatial workspaces.

### SCENERIO

Figure 1 captures a scenario wherein a user is engaged in an analytic map navigation task which involves extensive browsing, inspection and re-inspection of map items to make a decision. While touring a city, Adam decides to squeeze in a brief visit to a local museum. On his mobile device he queries for museums which are: i) open for the next hour; ii) has an entry fee within his budget; iii) is located at a short distance from his current location; and, iv) is reachable via public transportation. He opens the map browser on his smartphone and begins browsing through frequent panning and zooming, opening up information callouts for items of interest, and jogging in memory all the items he browsed. The entire process is physically demanding and has additional cognitive workload as he needs to remember the last visited best match to make a final decision. In contrast, with SAMMI, Adam opens up the map browser on his smartphone and pins his current location. With his non-dominant hand, the one on which he wears a smartwatch, he freely moves his finger in the space around the smartphone to access content in the workspace. While doing so, his smartwatch displays relevant information on museums that lay 'under' his index finger (Figure 1). As he finds museums which match his taste, he pins their callout on the smartphone with a mid-air pinch gesture. After completing his exploration, he revisits the pinned information on the smartphone to select a museum that best suits his criteria.

### RELATED WORK

Our work is inspired by recent results on spatially-aware navigation interfaces, multi-device coordination and multi-display systems on mobile devices. We also briefly review work done on workspace revisitation interfaces.

#### Spatially-Aware Navigation Interfaces

Spatially-aware navigation techniques present a viable alternative to the standard Flick-&-Pinch gestures for navigating virtual workspaces on mobile devices [20,26, 32]. Such techniques assume that the virtual workspace is pinned to the environment directly surrounding the user's device. On this premise, two dominant spatially-aware interaction metaphors have shown promise [20,30,34]. The Peephole technique, itself inspired by an earlier system, Chameleon [9], refreshes the mobile device's viewport with new content as the user moves the device up, down, left or right. In a recent study, Spindler et al. [32] compared peephole to the standard on-screen Flick-&-Pinch gestures for 2D document navigation tasks with two different sized mobile devices (i.e., iPhone 4, iPad 3). They found that with an optimized design, peephole navigation can clearly outperform the standard on-screen Flick-&-Pinch gestures. Even with a smaller screen display (e.g., smartwatch), Kerber et al. [21] found that the spatially-aware input is more useful than the traditional touch technique for map-based navigation tasks. Around-device pointing (AD-pointing) [14] shows on the mobile screen, content 'underneath' the user's mid-air finger. Recent work has shown that AD-pointing can benefit map browsing tasks in comparison to the traditional pan and zoom methods, particularly when content is properly organized in the space surrounding the device [14]. These navigation metaphors have largely been unexplored in emerging contexts where users are equipped with multiple mobile devices, such as carrying one or more smartphones, tablets or smartwatches.

These previous projects rely on external hardware to make the device aware of its periphery. Recently, researchers [20,31,33] have demonstrated the capability of detecting and tracking objects in the space around a mobile phone in real-time without depending on external devices. These prototypes are self-contained and spatial awareness is handled via the device's built-in camera [31,33] or using on-board sensors [20]. As devices are being designed for spatial awareness, a next step is to advance toward a new spatially-aware multi-device ecosystem without depending on external tracking methods. In our work, we assume that such environments will be common in the near future.

#### Multi-Device Coordination

Researchers have demonstrated novel interaction possibilities by connecting and synchronizing multiple devices. For instance, multi-device techniques have been devised to transfer and share files among devices without sending them manually [23] or to form a larger display by merging multiple individual devices [17]. The majority of these works have focused on non-spatial interactions where the devices' spatial information such as relative position and orientation are considered in limited contexts.

Recently, Chen et al. [5] proposed new interaction possibilities when coordinating in tandem sensors from a smartphone and smartwatch. Kray et al. [22] demonstrate the use of spatially-aware proxemics with a tabletop and mobile device to improve negotiation and coordination in group settings. While these works show new possibilities when synching mobile devices, they do not explore such coordination in the context of spatially-aware interfaces.

#### Multi-Display Systems

Recently, an increasing number of multi-display handheld devices have been proposed for improved interaction with smartwatches [24], phones [3] and tablets [16,17,25]. Furthermore, Grudin [11] observed that in a multi-display system, an auxiliary display can present secondary activities and facilitate quick access to information. We choose the 'always available' smartwatch as the auxiliary display as it can show small bits of information, which alternatively would be placed on the primary display, creating clutter. For example, in an analytic map navigation task, SAMMI shows various markers' information on the smartwatch, which can be transferred to the smartphone only if needed for future use. SAMMI's use of more than one device is largely inspired by these prior works suggesting quick access with an additional display.

### Workspace Revisitation

Studies reveal that interfaces such as web pages [1], lists and menus [13], involve repetitive usage patterns where users frequently return to previously visited items. Zhao et al. [35] found that with a map-based information seeking task, participants spent a significant amount of time revisiting previously viewed locations. Different techniques have been proposed to support revisitations such as bookmarks [35], histograms with visitation history [15], or modified visual features [29]. These techniques mainly provide cues to where the user might have visited but do not provide abstract information necessary to deliver insights during an analytic task [6,10]. In SAMMI we overcome this limitation by allowing users to 'pin' the necessary information for solving analytic tasks.

## DESIGN FACTORS

We outline a number of factors that are likely to influence the design of interactions and interfaces where spatially-aware mobile devices exchange position information to enable synchronization and operation in a spatially interlinked manner.

### Spatially-aware Navigation Interfaces

Large workspaces such as maps have an inherent spatial layout. Exploring such workspaces with spatially-aware interfaces has shown clear advantages over the standard on-screen Flick-&-Pinch gestures [20,26,32]. SAMMI aims at easing navigation in large workspaces by incorporating elements of two well-studied spatially-aware navigation interfaces, Peephole [9,34] and AD-pointing [7,14]. SAMMI's devices are spatially-aware; this creates an opportunity for refreshing the view's contents as in the peephole metaphor. However, users can also explore by simply moving one device while keeping the other still. As such, SAMMI presents an enhanced flavor of the AD-pointing metaphor.

### Device Combinations

SAMMI can operate using various device combinations, such as when the user has one or more smartphones, smartwatches, or other mobile devices. However, some combinations, and in particular pairs of devices, work better than others. First, combinations such as a smartwatch and smartphone may become more common than two smartphones. Additionally, operating more than two devices in a spatially-aware manner may be cumbersome in some scenarios, such as when a user is on a walk, or sitting in a busy bus. We focus our design on the combined use of a smartwatch and smartphone and leave the exploration of other combinations such as using more than two devices (e.g., smartwatch, smartphone and smart glasses) for future work. We also leave the exploration of using such device combinations in collaborative settings for future work.

### Usage Modes

Each device combination affords its unique set of usage modes. A SAMMI user with a smartwatch and phone can leave the watch on the left wrist or hold it with either hand. With a smartwatch on the wrist, at least two usage modes are possible. The first includes showing contents directly under the smartwatch while in the second usage mode the content under the user's index finger is shown. We also incorporate a 'Hold' style where users hold the smartwatch with one hand. This provides more flexibility to explore contents on the smartwatch and is not inhibited by the wrist range-of-motion [27]. We further investigate the effects of usage modes on navigation efficiency.

### Anchor Placement

Moving a mobile device, as in the Peephole, or moving the finger, as in AD-pointing, requires pinning the virtual workspace to a reference frame. In the peephole metaphor the workspace remains static, i.e., anchored to the world. With AD-pointing the finger moves in relation to a workspace anchored to the device. Since SAMMI inherits properties of both spatial navigation styles, we investigate the impact of anchor placement on performance.

### Feedback Type

Previous works [7,8,14] have demonstrated that the overall feedback about object locations in the workspace is essential for efficient navigation. With two devices, an additional feedback mechanism is necessary to show the location of each with respect to one another as well as to decide how to 'spread' information across the multiple displays. This led us to explore different feedback and information placement methods in our experiments.

### Selection Techniques

SAMMI allows users' to browse content on a virtual workspace with multiple spatially-aware devices. A suitable selection technique is necessary after the browsing phase to inspect an item in details. We are unaware of any selection techniques that have been investigated for such spatially tracked multi-device context. We explore two styles of selection techniques in our first experiment. One takes place on the device (e.g., tap or back-tap) and the other, off-the-device (e.g., a mid-air pinch gesture). Additionally, selection techniques could be facilitated by merging an Area Cursor-like approach [19] where the secondary device (smartwatch) always shows the information of the closest marker. This removes the need to explicitly open up markers, unless needed, and gives an additional 'hover-with-feedback' layer to such techniques. We applied this approach to the selection techniques.

## STUDY 1: DESIGN REFINEMENT

We conducted two initial sessions to inform our design of SAMMI. In the first session we explore Feedback Type and Usage Mode. In the second Session we explore Selection Technique and Anchor Placement.

### Session A – Usage Mode and Feedback Type

Very little is known about the usage modes when operating multiple smart devices such as a smartphone and smartwatch. Duet [5] shows a variety of interaction scenarios where the smartwatch is always worn on the wrist. However, users can also *hold* the smartwatch for quick access to information. This usage mode provides more flexibility and less fatigue as users can have more degrees-of-freedom for orienting the watch by rotating their wrist [27]. We include both scenarios in the next experiment, where the user holds the phone with the right hand while moving the left hand with the watch either worn on their wrist or held with the hand. We tested three usage modes – *Wrist*, *Hold*, and *Index* – as illustrated in Figure 2 and described below.

*Wrist* (Figure 2a): We asked the participants to wear a smartwatch naturally on their wrist. This usage mode was also used in [21] for operating a peephole on a smartwatch. However, navigation tasks in this mode may seem awkward, especially in regions of limited wrist flexibility. Another limitation is the constantly changing display orientation as the user moves their wrist in mid-air.

*Hold* (Figure 2b): To overcome the limitations mentioned in the previous usage mode, we included *Hold* where the watch is held in the left hand. While navigating a document, a user can correct the viewport orientation to suit their viewing angle. This mode also makes it possible to select items on the watch directly. It is also likely that if other spatially-aware devices were to be used, such as two smartphones, *Hold* would be the preferred usage mode.

*Index* (Figure 2c): This usage mode is similar to AD-pointing in that the left index finger is tracked. As with Wrist, the watch is worn but in this case the workspace content under the pointing finger is displayed. This provides more flexibility for navigating the workspace by exploiting higher degrees-of-freedom in finger movement.

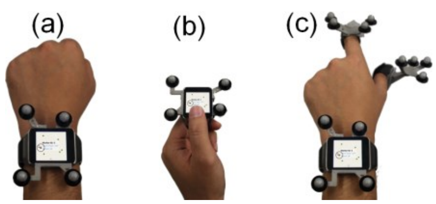


**Figure 2. Usage modes. (a) Wrist: the smartwatch is on the wrist; (b) Hold: the watch is held; (c) Index: while with Wrist and Hold modes the content shown comes from the region directly beneath the watch, with Index mode the content comes from the region beneath the index finger.**

We also explore different feedback styles as prior studies [7,8] have suggested a dependency on visual feedback while interacting with around-device objects. We show all feedback of item locations on the smartwatch. Given some of the clutter-related concerns with off-screen visual cues [12], we explore two feedback techniques, Overview and EdgeRadar [12]. We chose EdgeRadar as it leaves room in the center of the smartwatch display for showing marker content. The feedback about marker positions as well as the position of the watch is always presented on the smartwatch. The feedback indicates how close the watch is to all the targets in the workspace.

The *Overview* shows all the markers as well as the watch's position (Figure 3b). *EdgeRadar* provides a small overlay region along the edge of the screen to display off-screen objects as scaled-down proxies [12] (Figure 3c and 3d).

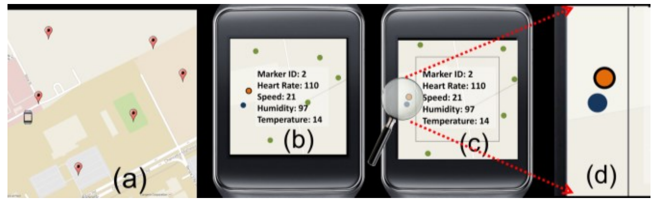


**Figure 3. (a) Map with six randomly placed markers. (b) Marker and watch positions (blue) on the overview where the entire map is resized to fit on the watch display. (c) With EdgeRadar, marker and watch positions are placed on the overlay regions along the edges (enlarged view in d).**

### *Participants and apparatus*

Nine male smartphone owners (21 to 37 years old) participated. Participation lasted approximately 60 minutes (including breaks and practice trials).

To ensure reliable and noise-free data, we used a Vicon tracking system (eight T-Series cameras) to emulate spatial awareness with our devices and around-device finger input detection. We used a Google Nexus 5 smartphone (with a 4.95-inch screen and a 1080×1920 pixels resolution) and a Samsung Gear Live watch (1.63-inch screen with a 320×320 pixels resolution). Software for the phone was built on Android 4.4.2 (API 19). The Android Wear API included in the Android v4 Support Library and Google Play services (revision 19) were used for the watch software. Google Maps Android API v2 was used to implement the necessary map-related features.

### *Task and study design*

We used a low-level task where the participant had to navigate a map to find a specific marker. A 50×38cm large area was used as the navigation region. The bottom-right corner of this area was pinned to the center of the smartphone. We asked participants to hold the smartphone with their right hand and explore the map markers with their left hand. For each visual feedback condition, six randomly placed markers were shown as green dots and the position of the pointing device (watch or index finger) was indicated with a blue dot. The markers contained various information pieces, such as marker ID, heart rate, humidity, jogging speed, and temperature. The task consisted of locating the 'target marker' with a certain ID ("find the marker with ID 3"). To assist the selection, we used a variation of the Area Cursor [19] where information about a marker was displayed on the watch screen and the color of a marker was changed to red with a black border when the pointing device was moved within five centimeters from a marker. We decided to use this value as it is similar to the watch screen size and we wanted to show a marker's information whenever the pointing device was close to a marker. If more than one marker was within the area cursor's activation range, the information from the closest marker was displayed. To keep the visual feedback techniques consistent, we did not rotate the screen content on the watch to align it with the user's viewing angle while users moved their arm. The entire workspace and its details were visible on the watch with the visual feedback techniques. To begin a trial, the participant pressed a Start button on the phone. With all usage modes, a trial ended with a double-tap on the back of the smartphone (backtap is a promising selection method for around-device interaction [14] and taps on the screen should be restricted to interactive on-screen content). A trial was only terminated after a double-backtap if the target marker was open on the watch screen. The target location was randomized and no feedback was given when participants selected a non-target marker.

We used a 3×2 within-subjects design with Usage Mode (*Wrist*, *Hold*, *Index*) and Visual Feedback (*Overview*, *EdgeRadar*) as factors. Each participant performed 18 trials with each Visual Feedback-Usage Mode combination, resulting in 108 trials per participant. Participants completed five practice trials before the test trials. The presentation order of the Visual Feedback-Usage Mode combinations was randomized among participants. We asked participants to perform each trial as quickly and accurately as possible. After completing all methods, participants rated for preference.

### *Results*

The mean trial times are shown in Figure 4. A RM-ANOVA showed trials with *Overview* were significantly faster than trials with *EdgeRadar* ($F_{1,8} = 10.2$, $p < 0.05$, $\eta^2 = 0.56$). The usage mode did not affect trial times. There was no significant *feedback-mode* interaction effect. The advantage of the *Overview* is also evident in participants' preference ratings: seven preferred *Overview*, two preferred *EdgeRadar*. Most participants commented that the position feedback provided by *Overview* was easier to interpret than *EdgeRadar*'s position feedback.

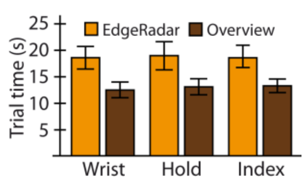

**Figure 4. Trial time. Error bars: ±2 S.E.**

Participants were unanimous against *Wrist*-mode: all rated it as the least preferred usage mode. Participants were split about *Hold* (5) or *Index* (4). Participants commented that *Hold* provided the most flexibility, having the watch on the wrist – as with the *Wrist* and *Index* modes – often caused awkward viewing angles and constrained arm movements. Constrained arm movements could, however, be adequately mitigated through bending and adjusting the pointing finger when *Index* mode was used.

From these results we move forward to evaluate two other design factors in Session B, which aimed at identifying suitable selection techniques and anchor placement styles.

### Session B – Selection Technique and Anchor Placement

Hasan et al. [14] explored different methods for selecting items in around-device space. However, these methods were implemented for a single device case. As selection of items under the smartwatch largely depends on the usage mode, we explore three different selection techniques that support the three usage modes listed in Session A.

*Hold+Tap*: is a quick tap anywhere on the screen using the thumb when the watch is held in the hand. This selection technique can be used while a smartwatch is being held in the hand (*Hold*). We include this technique as it requires minimum thumb movement for selection while holding the watch with one hand.

*Index+BackTap*: triggers selection when a tap on the back of the smartphone creates a spike in the device's accelerometer. After experimenting with various thresholds we found two 4 $m/s^2$ peaks with a lower value in the middle (similar to a sine wave shape) to be suitable for a double-tap detection. We choose the back-of-the device selection as it eliminates the risk of invoking interactive items on the screen during a selection. Conversely, a backtap cannot be used when the device is placed on a table.

*Index+Pinch:* involves pinching the index finger and thumb in mid-air. The selection is triggered when the fingers are less than 2cm apart. It provides the freedom to carry out the selection anywhere instead of restricting it on device. This selection technique can be used with *index* usage mode.

We also compare the effect of two anchor placement styles. We compare the interface used in Session A, where the workspace was anchored to the phone (*Device* anchor), to the use of an external anchor point (*External* anchor).

With the *Device* anchor, the content displayed on the watch is based on the relative distance from the phone. Consequently, movements of the phone influence what is shown on the watch. In contrast to this, with an external anchor point (or world-fixed anchor), the content shown on the watch is independent from the current position of the phone. *External* fixes the anchor point in physical locations in the real world. In this anchor placement mode, users are allowed to use both devices, as peepholes, to search information on the map. Two icons on the overview are used to show the respective smartphone and smartwatch positions on the map. Also, the marker information was doubled, as shown in Figure 5: both information from the marker closest to the watch (*Hold+Tap*), resp. index finger

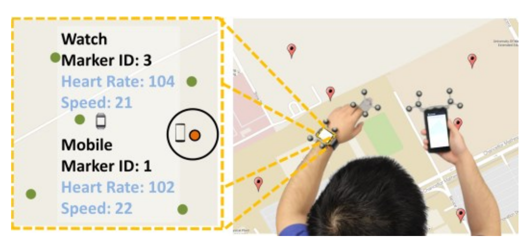

**Figure 5. With an External anchor placement, information of markers closest to both devices is shown on the watch.**

(*Index+BackTap and Index+Pinch*), and information from the marker closest to the phone were visible on the watch.

### *Participants and apparatus*

Eight smartphone owners (21 to 36 years) participated in a session lasting roughly 50 minutes, including breaks and practice trials. The apparatus was the same as in Session A.

### *Task and study design*

We used the superior *Overview* from Session A to provide feedback about marker positions. The task was the same as in Session A: six markers were randomly placed on a 50×38cm large map area and the participants were asked to find the marker with a certain marker ID. Participants always held the smartphone with their right hand while holding or wearing the watch on their left hand. The bottom-middle point of the region was placed in front of users (*External* anchor) or centered on the smartphone (*Device* anchor). We also dynamically rotated the content on the smartwatch so that it aligned with the user's view. To assist with selection, we used an area cursor, as in Session A. With *Device* anchor, marker information was displayed on the watch when the pointing device (i.e., index finger alt. watch) was moved within five centimeters from a marker. A circle in the Overview highlighted the 'current' marker. With *External* anchor, information from two markers can be displayed at the same time, one for the smartwatch and the other for the smartphone, as these devices get within a certain distance to a marker. However, only the closest marker to either device is selectable. A circle in the Overview highlighted the selectable marker, as shown in Figure 5. A trial started when the start button on the smartphone screen was pressed. A trial ended with a correctly performed selection action while the information from the target marker was displayed on the watch. Selections of non-target markers were ignored.

We used a 3×2 within-subjects design for *Selection Technique* (*Hold+Tap*, *Index+BackTap*, *Index+Pinch*) and *Anchor Placement* (*External*, *Device*). Participants performed 18 trials with each of the six combinations of *Selection Technique* and *Anchor Placement* for a total of 108 trials per participant (864 in total). The presentation order of *Anchor Placement* was counter-balanced among participants. The target marker was positioned at a new random location in each trial. Participants were instructed to finish trials as quickly and accurately as possible. Preference ratings were collected at the end of the session.

### *Results*

The mean distance the watch and the phone were moved during a trial is shown in Figure 6a. Unsurprisingly, when the map was anchored to the phone (*Device*) the watch movement dominated that of the phone. We saw small movements of the phone as the participants adjusted the device in some situations (e.g., reaching the furthest item) to access the targets more conveniently. When the map was anchored to an external reference point (*External*), however, we see that the participants also moved the phone for searching markers. Both the phone and the watch were moved equally long distances during a trial.

Whereas an external anchor placement provides movement flexibility that can be used to avoid uncomfortable arm positions, with the left arm, it does not reduce the navigation time, as visible in Figure 6b. A RM-ANOVA confirmed with no significant effect of *Anchor Placement* on trial time. As noticed by most participants, an external anchor demands more careful coordination between the hands during navigation. It also requires the user to keep track of the two proxies on the overview, which is likely to be mentally more taxing and time consuming.

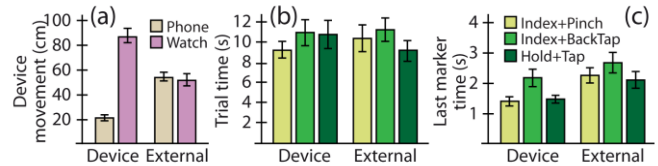


**Figure 6. a) Device movement distance, b) trial time, and c) last marker time. Error bars: ±2 S.E.**

The ANOVA also showed that the selection technique did not influence trial time. It is possible that differences between the three techniques are masked by the long navigation time. Differences between the selection techniques emerge when we examine the times for the final part of each trial, i.e., from the instant when the information from the target marker was last displayed on the watch to the end of a trial. We refer to this as 'last marker time' (Figure 6c). During this final part the participant had to recognize having found the target marker and needed to select the marker and end the trial with either a Pinch gesture, a double backtap on the phone, or a tap on the watch. A RM-ANOVA showed shorter times with *Device* than with *External* anchor ($F_{1,7} = 8.7$, $p < 0.05$, $\eta^2 = 0.55$) and a significant difference for *Selection Technique* ($F_{2,14} = 13.2$, $p < 0.001$, $\eta^2 = 0.65$), but no interaction effect. Bonferroni adjusted post-hocs showed that *Index+BackTap* was significantly slower than both *Index+Pinch* and *Hold+Tap* (p's < 0.016), which did not differ.

The longer last marker times with the External anchor are caused by an additional decision and movement phase. With a Device anchor, the participant could immediately issue the selection action as soon as the target information appeared on the watch display, but could not do so with an External anchor. Instead, the participant had to also infer which of the two markers, the one closest to the watch or to the phone, would be selected when issuing the selection action. The longer last marker times with *Index+BackTap* are explained by having to register the selection, which requires two taps, and is longer than a mid-air pinch.

Participants were divided about anchor placement and selection techniques. Four preferred the external anchor and four preferred having the workspace anchored to the phone. Six rated the *Hold+Tap* to be the best alternative. When deciding between selection techniques for index-pointing, six preferred *Index+Pinch*, two *Index+BackTap*.

## STUDY 2: ANALYTIC MAP NAVIGATION TASK

While one goal of our work was to identify how best to design two spatially interlinked smart devices, another goal was to study whether such an interface facilitates analytic map navigation tasks. Accordingly, we evaluated SAMMI against the traditional touch input, which includes Flick-&-Pinch gesture for navigation.

### Participants and Apparatus

Twelve smartphone owners (2 female, 21 to 36 years old) participated. Two had participated in either of the previous sessions. The same apparatus was used as in Study 1.

### Task, Experiment Data and Experimental Design

The analytic task simulates a frequent situation where a user has queried a system for information. The task involves a two-phase approach where in the first phase the user searches for specific content on the map and pins the content of markers (callouts) for further inspection and comparison. A second phase involves a matching task where users need to check information from the callouts to answer a question. Such a task is analogous to methods for visual analytic provenance [10] wherein a history of incremental decisions aids with the overall task goal. This approach is common when a user searches and compares pieces of items on a web page, or when comparing values and properties of homes on a map. Such tasks are also common when a search criterion is composed of several unknown attributes, and whereby manual inspection of relevant information is necessary. We consider this task to be complex as it involves tedious navigation, selection and re-inspection. To our knowledge, spatially-aware interfaces have not been evaluated with such forms of analytic task.

We first implemented an application to collect realistic data for our experiment. Data was collected from a mobile device while one person was walking, running or biking in a park. A Samsung Gear Live smartwatch also provided heart rate data. The application collected GPS coordinates, altitude information, heart rate, information about what music was played, and what pictures were taken. We used this data to ask questions involving map navigation and information retrieval. Sample questions included, '*What songs were played when walking speed was low?*', '*What heart rates were registered when listening to music from U2?*', and '*What altitudes were measured when the heart rate was high?*'

A trial starts with a question displayed in the middle top of the smartphone screen. After reading the text, the participant taps a Start button and trial time begins. The question text moves to the top of the screen for constant recourse, as shown in Figure 7b. With the Touch condition, the next screen shows the park on a map with markers.

Map markers contain activity information (walking/running/biking at low/mid/high speed), recorded heart rate values, the played music track, thumbnails of captured images, and altitude information. Marker information is displayed in a callout box through a tap on the corresponding marker. Panning and zooming of the map are fully enabled. Participants were informed that they could pin marker information on the screen (Figure 7c) for later use by directly tapping on the callout.

We used *Index mode* for navigation with SAMMI. The information of the marker currently enclosed by SAMMI's area cursor is shown on the smartwatch (Figure 7a). Pinning marker information to the smartphone is done with a Pinch gesture. As this task primarily involves browsing and selecting items and as the *Device* anchor placement requires less time when selecting markers placed around the smartphone, we chose to use the *Device* alternative for SAMMI. We used an overview on the watch to display map markers and to indicate the current marker, as shown in Figure 7a.

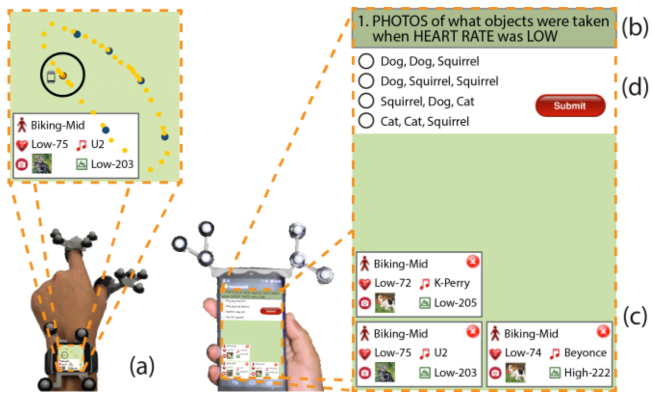


**Figure 7. Information about what marker is currently active is shown on the overview (a). The user navigates the map to find and pin the three markers needed to answer the task question (b). The user can pin a callout by pinching the index finger and thumb, and the callout is placed on the smartphone screen for later use (c). A tap on the question text (b) opens a dialog with four answers (d). The user selects an answer and confirms by pressing the submit button (d).**

In each trial, which had either 6 or 12 markers in total, participants had to pin and compare information from exactly three markers in order to correctly solve the task question (for each trial the marker information was modified to exclude learning effects). We limited the required number of markers to three so as not to crowd the smartphone screen, which would give an unfair disadvantage to the Touch condition (where screen space is needed to interact with the map).

When a participant believes having pinned the three markers that closely match the search criteria, s/he taps on the question text at the top of the screen. This opens a dialog box with four possible answers (Figure 7d). We stop recording navigation time when the dialog appeared. The trial time is logged when the user selects the proper answer. The experiment lasted about 45 minutes (with breaks and practice trials).

We used a 2×2 within-subjects design for factors *Technique* (Touch, SAMMI) and *Number of Markers* (6, 12) that contain information. Participants performed eight repetitions for each combination of factor levels, for a total of 32 timed trials per participant (a few practice trials were given per interface). The *Technique* was counterbalanced across participants and *Number of Markers* was presented in random order within each interface.

The total trial time (from trial start until the correct answer is submitted) is split in two segments: *Navigation time* and *Answer time*. Navigation time is measured from trial start until the three relevant makers are pinned on the phone display. Answer time captures how long the participant needs to deduce and submit the correct answer once all relevant markers have been pinned.

#### Results

We removed 15 outlier trials (3.9%) with a trial time > 4 s.d. from the corresponding mean time (the outliers were about equally distributed between the four *technique-marker* combinations and participants). A total of 369 trials remained. The means for these trials is shown in Figure 8.

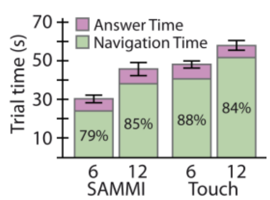


**Figure 8. Trial time. Error bars: ±2 S.E.**

The mean answer time was 6.9s. Unsurprisingly, the *Answer time* was equal for all *technique-marker* combinations (i.e. neither the technique nor the number of markers influenced how long it took participants to deduce and commit the right answer). More interesting, a RM-ANOVA showed that the navigation time was significantly different depending on both the *Technique* ($F_{1,11} = 40.2$, $p < 0.0001$, $\eta^2 = 0.79$) and the *Number of Markers* being searched ($F_{1,11} = 108.4$, $p < 0.0001$, $\eta^2 = 0.91$). Navigating with SAMMI was 27.6% faster than with Touch (32.8s vs. 45.2s). Users were slower when the number of items doubled. There was no significant *Technique*×*Number of marker* interaction. The efficient navigation and information comparison provided by SAMMI is accentuated by the fact that with 12 markers SAMMI was as fast as Touch with only 6 markers.

### DISCUSSION

Our results show that in comparison to Flick-&-Pinch, SAMMI facilitates improved performance on an analytic map navigation task. We attribute this to a few factors. First, we believe the ability for users to 'glance' at items of interest, by positioning their index finger at the right place in the workspace, and viewing content on the smartwatch is key for improved task performance. In contrast, with the Flick-&-Pinch interface, users have to select a target, view the content in a callout, and then close it. SAMMI entirely by-passes these micro-steps by having the smartwatch present the necessary callout information. Second, as users browse with their index finger, having the feedback directly in the region of exploration minimizes the overhead accumulated through switching between the screen on the smartwatch and that on the smartphone. SAMMI was specifically designed to reduce such forms of divided attention and we believe this contributed in part to the performance we observed. Finally, we provide selection in mid-air using a Pinch gesture. This does not involve selecting small targets, thus making it less effortful and more efficient when completing the task.

A limitation of our study concerns the type of content we used. As task variations can affect outcomes with spatially-aware interfaces [26], future work is needed to study SAMMI under multiple forms of analytic tasks.

#### SAMMI Limitations

*Virtual hover.* SAMMI provides a virtual hover state with feedback. This is useful to inspect target items without having to open them. However, such a state can disrupt users' operations as we observed when participants would open unwanted target items as they hovered around the workspace. This partly explains the slowdown with SAMMI when the workspace contained 12 markers.

*Divided attention.* We explicitly shifted all the necessary information, i.e., both the overview as well as item information, onto the watch display to limit divided visual attention issues. The user simply has to follow their moving hand to do most of the navigation and content inspection. However, when the information is spread across both displays, such as having the pinned information on the smartphone for later use, users showed a slight degree of confusion, especially early on in the experimental trials. This confusion diminished after a few trials. Additional feedback mechanisms, such as vibrotactile cues, might be useful to signal where information resides.

*Handedness.* In our exploration we configured SAMMI using a smartwatch and a phone. The watch is worn on the left hand, thus requiring users to keep the phone in their right hand. Spatially-aware interfaces can be affected by handedness [26]. Accordingly, careful examination is required to explore such issues with SAMMI.

#### Design Considerations

Designers of spatially-aware multi-mobile interfaces could benefit from the following considerations:

- *Direct feedback.* Placing feedback about item locations as well as information content directly where the user is pointing can facilitate rapid workspace navigation.
- *Index finger as proxy.* Interacting with the index finger is preferred over holding the secondary device (in our case the watch) to show relevant content. This mode of operation leaves the index finger available for other forms of interaction, such as pinching to trigger selection.
- *Display Orientation.* Feedback on the secondary device, such as a watch, needs to be adjusted according to how this device is held, such as re-orienting the view to match that of the user.

- *Workspace Anchor.* Anchoring the workspace to only one device can be as effective as when the workspace is anchored to world coordinates.
- *Feedback and Selection.* Familiar feedback methods such as an overview, are likely to be better understood than less conventional mechanisms (*Edgeradar* in our case), even if the latter frees-up more display space. A pinch gesture is an efficient and natural selection technique for around-device interaction.

## Potential SAMMI Applications

We discuss other potential applications that can benefit from SAMMI.

*Advanced AD-Interactions.* With SAMMI, content can be placed much more freely as one need not be concerned about occupying screen space on the primary device. Instead, the user can quickly scan the space around the device, relying not only on their spatial memory, but also on the feedback made available on the secondary device. This feedback can assist in being a scaffold for learning about where content may reside in the workspace. Additional studies are necessary to investigate how users build their spatial model of the workspace when such feedback is directly available at the "point of contact" instead of having it on the primary device.

*Video browsing.* Browsing videos on mobile devices still employs an age-old paradigm that relies on a slider and buttons for play and pause. Scrolling through videos has been made easier recently, but mainly for desktop systems [27]. Such techniques may have limited operability on mobile devices. For example, scrubbing the video thumb to a new location will in effect 'move' the video to that frame. Reverting back to the original position can be arduous. However, with SAMMI, a timeline can be placed with *Device* anchor style and the user can browse the video frame-by-frame on the watch using various locations along the timeline, as visualized in Figure 9. The user can first inspect the video sequence 'under' the finger before moving the video ahead (or back), using a mid-air pinch gesture.

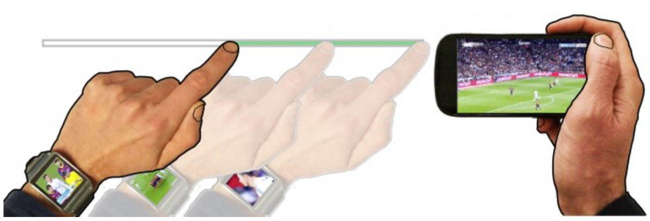

**Figure 9. Video browsing with SAMMI. As the smartwatch is spatially tracked, videos frames are made visible on it for allowing the user to quickly move within the video.**

*Browsing large image catalogs on mobiles.* Browsing images on mobile devices can be tedious, as content can be organized using hierarchical structures. Using SAMMI, we envision a large catalog of images spread around the device. Moving the finger in this space could open up the folder's contents onto the secondary device. With techniques such as rapid serial visual processing (RSVP) [4], images can flip in sequence, on the smartwatch.

*Coordinated mobile devices for collaboration.* Our work with SAMMI considered only one user. However, one potential application would be to use SAMMI for collaborative analytic tasks on large workspaces [8] where multiple collocated users could work on a shared workspace to achieve a goal. Such interactions resemble our interface in Session B, with an external anchor placement. However, additional feedback mechanisms may be necessary to provide suitable awareness about each user's actions.

*Multi-layer information presentation*. Though SAMMI has been demonstrated for 2D navigation tasks, it could be potentially extended for multi-layered interactions. Multi-layer information such as Google map view, street view and earth view could be placed on different layers on top of the primary device and users could get different views by moving the secondary device over the layers.

## CONCLUSION AND FUTURE WORK

We proposed SAMMI, a Spatially-Aware Multi-Mobile Interface that is based on principles of Peephole and Around-Device navigation techniques. We implemented a version of SAMMI using a smartwatch and a phone – as in our example – that are spatially interlinked. Through an exploration of SAMMI's design space we have identified properties of various design factors relevant to SAMMI-like interfaces. In our final study, we found that SAMMI can facilitate analytic tasks and that it provides an efficient interface for navigating workspaces with significant information content. Our future work will consider investigating SAMMI under constrained environments, for example when the around-device interaction space is limited due to social acceptability concerns [2]. We will also explore SAMMI using fully self-contained approaches, such as Surround-See [33]. Furthermore, we plan to investigate SAMMI with a range of analytic tasks, in applications other than map browsing, such as video navigation and image management.

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